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Quantifying Cyclists' Power Associated with Frame Flex While Pedaling

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Abstract: As a cyclist pedals a bicycle, the cyclist's forces imposed on the bicycle cause the frame to flex. Thus, some amount of the cyclist's overall effort is lost to the frame's flexibility. The question remains: how much effort is actually lost? Frame flex herein considers the frame only excluding the fork and seatpost. To quantify the power required to flex the frame published data of a cyclist's forces imposed on a bicycle for three riding scenarios was utilized: 'speeding' (rider seated, 255 Watts of power at the pedals), 'hill climbing' (rider not seated climbing a ten percent incline, 665 Watts), and 'sprinting' (rider not seated, an estimated 1609 Watts). Published data of empirically measured lateral flexibility of front and rear triangles of 62 on-road bicycle frames was consulted to determine representative minimum, average, and maximum flexibility of front and rear triangles. Computer-Aided Design and Finite Element Analysis was then used to simulate the resulting frame flex of a frame with average front and rear flexibility under the three riding scenarios. The associated power required to flex the frame for the three riding scenarios was calculated to be—1.6, 9.0, 47 Watts respectively representing 0.6, 1.3, and 2.9 percent of the power output at the pedals. The maximum power penalty associated with pedaling the most flexible frame versus the stiffest frame was coincidentally numerically close to the above reported values—1.7, 8.9, and 47 Watts representing 0.6, 1.3, and 2.9 percent of the power at the pedals. Up to an estimated 820 Watts of power at the pedals, the maximum power penalty is less than the power losses of the most efficient drivetrains (chain and derailleur). The power required to flex the frame as a percentage of power at the pedals is conservatively high since the metabolic power of the cyclist's upper body as a form of leverage on the handlebars to increase the downward force on the pedals was not included as part of the power at the pedals. It is estimated that no more than 40 percent of the power required to flex the frame is available to be returned in the form of propelling the bicycle forward.

Keywords: Bicycle Frame; Flex; Deflection; Energy; Power

1. Introduction

The purpose of this study is to quantify a cyclist's power associated with frame flex. Frame flexibility herein consists of the frame only excluding the seatpost and fork. The cyclist's power required to flex a frame is defined as the outcome of the cyclist's forces imposed on the bicycle that cause the frame to flex while pedaling over smooth surfaces. With the exception of Footnote #1, to the best of the author's knowledge estimates of such power have not been previously published.

The key finding of the present study was that the estimated maximum power penalty associated with a cyclist pedaling the most flexible frame compared to the stiffest frame is less than the power losses of the most efficient drivetrains (chain and derailleur) up to an estimated 800+ Watts of power at the pedals. The power penalty is small enough that the possibility a more flexible frame could be faster than a stiffer frame cannot be ruled out.

2. Methods[1]

2.1 Energy and Power Equations

The energy to deflect a spring is defined in Equation 1 (Avallone, & Baumeister III), which does not include internal energy losses (i.e. hysteresis losses) on the order of five to ten percent TEVEMA (2024). Energy (E) has the units of Joules, force (F) units of Newtons, and deflections (d) units of Meters. Cos(θ) accounts for the vector component of force in the direction of the resulting flex, where θ is in radians and represents the angle between the direction of the force and direction of the deflection. Equation 1 is valid so long as the internal stresses of the material remain beneath the material's Yield Strength (i.e., the spring is not overstretched and permanently damaged).

$$E = ½\,Cos(\theta)\ * F\ * d, \qquad \text{Equation (1)}$$

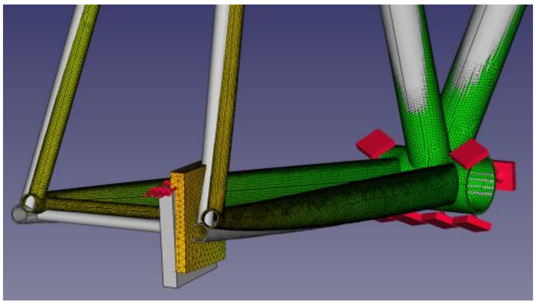
Herein forces (F) and deflections (d) will always be reported in the same direction thus θ=0, Cos(θ)=1. Equation 1 simplifies to Equation 2. Equation 2 applies to a bicycle frame for all commonly used materials such as steel, aluminum, titanium, and carbon fiber.

$$E = ½\,F\ * d, \qquad \text{Equation (2)}$$

To apply Equation 2 to a bicycle frame, consider the case of a rider pushing down on the pedals creating chain tension that pulls on the rear cog. In Figure 1 the cog (depicted as a rectangle but does not affect the results) shows chain tension as red arrows pointing forward. The gray surfaces are the frame when it is not flexed, and the orange/green surfaces are the frame when fully flexed.

The chain tension is modeled as 3926 Newtons (883 lbs.)[2] representing the extreme condition of sprinting. The bottom bracket is depicted as clamped, allowing the chain tension at the rear cog to flex the rear triangle. Section 2.3 explains why modeling the bottom bracket as clamped results in valid findings. The frame's overall design and tubing are also described in Section 2.3. Figure 1 highlights that the rear triangle flex due to chain tension is complex including side-to-side (about 6-mm in this example), upward, and forward. Not immediately apparent in Figure 1 is that the entire frame flexes to some extent.

Figure 1. Rear triangle flex due to chain tension.



All the frame flex in Figure 1 is the result of the energy added to the frame. Regardless of the complexity of the frame flex, the energy calculated when using Equation 2 would be based on the magnitude of the chain tension force (F) and the deflection (d) that the top of the cog flexes (shifts) in the same forward direction as the chain tension.

To translate energy into power Equation 2 is multiplied by two to account for the frame flexing twice with each full pedal stroke. Equation 2 is also multiplied by the term 'Cadence RPM / 60', which is the number of full

[1] BikeForum.net, message thread "Where are the numbers relating stiffness to speed or power?" Mark Kelly (Post 15893791, 07-27-13 07:13 AM) describes a methodology that inspired the present study. Kelly concluded for a defined scenario that a cyclist's power required to flex a frame is 0.54% of power at the pedals. tomato coupe's reply (Post 15895031, 07-27-13 04:11 PM) suggests the need to cover a wider range of scenarios.

[2] Soden & Adeyefa (1979) found a maximum downward force on a pedal 1815 N (408 lbs.), 2.75X the rider's weight, due to the rider pulling/pushing on the handlebars as leverage. The pedal force is leveraged to 3929 N (883 lbs.) due to the ratio of the crank length to the chainring radius estimated by this author.

pedal strokes per second. The result is Equation 3, which expresses power (P) in Watts.

$$P = F * d * Cadence\ RPM/60, \qquad \text{Equation (3)}$$

In the case of multiple forces applied to the frame the calculated energy (or power) for each applied force in the direction of each force are summed.

2.2 Quantifying Frame Flexibility

To quantify a typical amount of frame flexibility a dataset of 62 on-road frames (Rinard, 1995) was referenced and the average front and rear triangle flexibility calculated. Although the dataset was collected 30 years prior it was preferred since it focuses on the frame only and the test methodology is readily repeatable by many in the cycling community.

One question concerning the data is whether meaningful changes in frame flexibility have occurred since. We may consult indirect evidence to confirm, or not, the above conclusion.

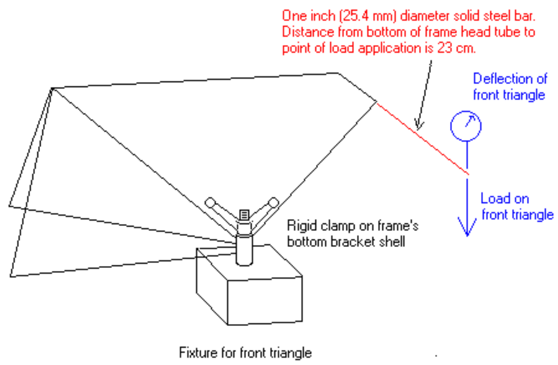
For example, safety regulations (Requirements for Bicycles, 2024) effectively place a lower limit on tubing diameters and wall thickness (which vary by frame material) to meet minimum strength requirements, thus effectively placing an upper limit on frame flexibility. A reinforcing constraint is the need for performance orientated frames to retain a minimum level of stiffness necessary for predictable steering under hard cornering.

The incentive for manufacturers to reduce material costs and/or reduce weight conversely has the effect of placing a lower limit on frame flexibility. Lastly, 100+ years of frame design had arguably reached a very mature state by the 1990s. For all the reasons discussed it was decided to move forward with the flexibility data.

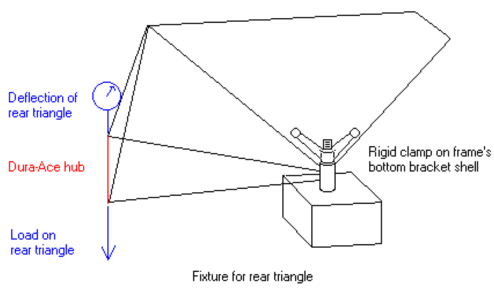
The test method to measure flexibility used a 21.6 kg (47.5 lbs.) weight to laterally flex each frame's front and rear triangles; Figures 2a and 2b. Constraining the bottom bracket shell as shown, orientating the frame horizontally, and hanging a weight off the front and rear triangles eliminates the need for pulleys that introduce hysteresis effects (Vanwalleghem et al, 2014) and negates the need for actuators that add cost and require calibration. The test method is inexpensively repeatable by any frame builder having an existing alignment table and displacement gauge, which is how the data was originally gathered.

Figure 2 (a) and (b). Frame flexibility methodology used by Rindard (1995).

(a)



(b)



The 62 on-road frames were traditional diamond shaped without active suspension made from steel (35 count), aluminum (4 count), titanium (17 count), and carbon fiber (6 count). The bicycle brands included were Specialized, Trek, Cannondale, Pinarello, DeRosa, Klein, Kestrel, LeMond, Holland, Tesch, Masi, Serotta, Paramount, Tomasso, Bob Jackson, Eddy Merckx, Casati, Richard Sachs, Medici, Guerciotti, Hedgehog, Schwinn, Rigi, Centurion, Behringer, J. Durso, Merlin, and Litespeed.

Since titanium frames were overrepresented as 27 percent of the sample size

the following graphs were divided into titanium frames and non-titanium titanium frames. Figure 3 indicates that frame sizes versus the number of bicycles in each size range is well distributed from XX-Small (50 cm) to XX-Large (76 cm) with most frame sizes in the medium size category.

Figure 3. Distribution of frame sizes.

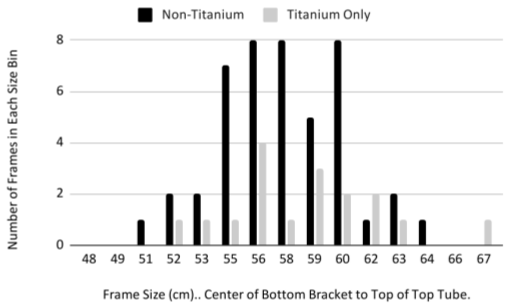
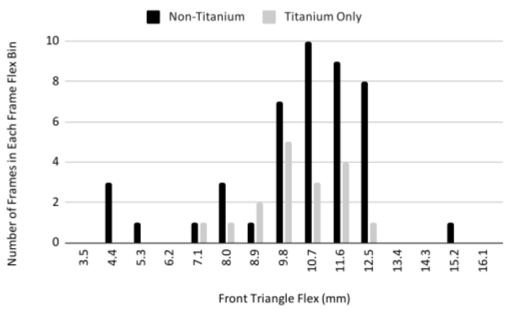


Figure 4 shows the distribution of front triangle flexibility and number of frames in each flexibility range bin. Titanium frames showed no tendency towards higher flexibility although titanium is inherently more flexible (lower Modulus of Elasticity) than steel. A provided explanation was that the producer of the majority of titanium frames used larger diameter tubing in the front triangle versus that of steel frames. This has the effect of compensating for titanium being more inherently flexible.

Figure 4. Distribution of front triangle lateral flexibility.

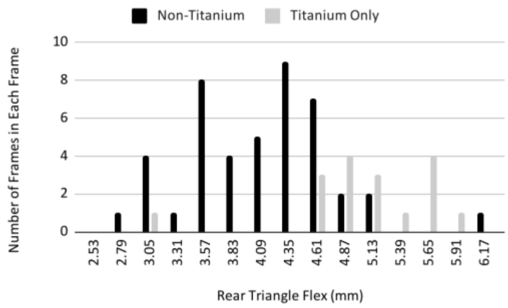


The frame with the most flexible front triangle was a steel Columbus Air tubing frame and was removed from the dataset due to its anomalous narrow profile tubing seen in Figure 5 (The Radavist, 2010). The three stiffest (least flexible) front triangles were aluminum and were not removed from the dataset.

Figure 5. Extremely narrow Columbus Air tubing.

Figure 6 shows the distribution of rear triangle flexibility in which titanium frames show a tendency towards higher flexibility. This effect was not noted by the author of the dataset. No explanations are proposed here. In light of the tendency to exhibit greater levels of rear triangle flexibility and being oversampled all the titanium frames were kept since the most flexible rear triangle was in fact steel. Removing all the titanium frames only decreases the average rear triangle flex by six percent.

Figure 6. Distribution of rear triangle lateral flex.



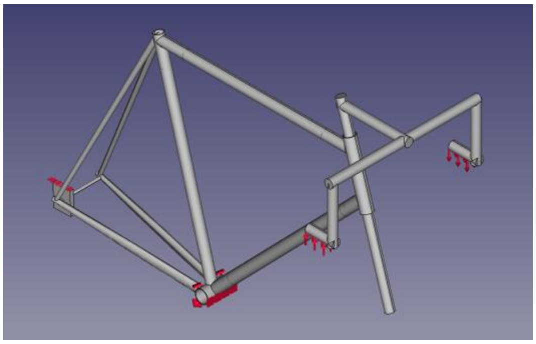
For all these reasons the data was deemed to be a reasonable representation of the range of flexibility found in bicycle frames. As working numbers, the minimum, average, and maximum front triangle flexibility was 3.6, 9.9, 15-mm. Minimum, average, and maximum rear triangle flexibility was 2.5, 4.3, and 6.1-mm. From the

above front triangle lateral flexibility varied 4.2X, and rear triable lateral flexibility 2.4X.

2.3 Reference Bicycle Frame

Computer Aided Design was used to design a drop bar steel (Modulus of Elasticity 205 GPa) racing frame with a geometry matching the frame used in published estimates of a cyclist's forces imposed on a bicycle (Soden, & Adeyefa, 1979), Figure 7. Tubing profiles were based on those found in Columbus's 2019 catalog as follows; top tube 28.6-mm diameter double butted 0.8/0.5/0.8-mm wall thickness; seat tube 28.6-mm diameter triple butted 0.75/0.4/0.6-mm (bottom/middle/top); downtube 31.8-mm diameter double butted 0.9/0.6/0.9; chainstays 24-mm diameter (ovalized 18 x 28.5) at the bottom bracket, 13.5-mm diameter at rear dropouts, 0.7-mm straight gauge wall thickness; seat stays 17-mm diameter at the seat tube, 11.8-mm diameter at rear dropouts, 0.5-mm straight gauge wall thickness.

Figure 7. Simulated bicycle frame showing the location of the three forces from Table 1.



A solid steel rod was included passing through the head tube and held in place with mock head tube bearings to match Rinard's (1995) methodology. The steel rod also extended upward to serve as a steerer tube for a stem and handlebars. The stem and handlebars were also modeled as solid steel rods, as well as the rear axle, so that deflections would be that of the frame only. The Finite Element Analysis was configured to ignore the weight of the frame and solid bars. The bottom bracket shell was simulated as being rigidly clamped per Rinard (1995).

The reference frame was simulated then calibrated to within 1 percent of the average levels of front and rear triangle flex by reducing the diameters of the top tube, downtube, seat tube by 5.5%, and reducing the diameters of the chainstays and seat stays 13.5%. Wall thicknesses were held constant.

2.3 Forces on The Bicycle Frame

Table 1 shows a cyclist's forces at the handlebars, pedal cadence, and power applied to the pedals as was reported by Soden & Adeyefa (1979) for two of the author's three scenarios; speeding while seated and climbing a 10 percent gradient while not seated. Soden's third reported scenario was 'starting' from a standing stop. The starting scenario was converted to a sprinting scenario discussed further down. Two of the values in Table 1 under the sprinting scenario are italicized and underlined to indicate they were derived within this report.

Table 1. Forces, pedal cadence, and power at the pedal for the three riding scenarios.

	Speeding	Climbing	Sprinting
Forces (Newtons)			
Right Handlebar (up)	71	235	714
Left Handlebar (down)	-101	-181	-293
Chain Tension on Rear Cog	516	1623	3929
Cadence RPM	89	76	*76*
Power at the Pedals (Watts)	255	665	*1609*

Forces in Table 1 are maximums at the moment the pedal cranks are horizontal. For all three riding scenarios the chain tension was calculated in this report based on reported forces applied to the pedals, crank length, and estimated chainring diameter that itself was based on reported gearing (reported as gear inches) and whether the large or small front chainring was engaged based on photos.

The estimated chainring diameter and reported gearing was then used to estimate the rear cog diameter. Based on a typical 126-mm rear axle from the time period the rear cog's location along the rear axle was estimated.

Soden & Adeyefa (1979) did not report pedal cadence and power output at the pedals for a starting scenario since the pedal force was measured for just one full pedal stroke. For this analysis a sustained pedal cadence of 76 RPM was assumed and the scenario was renamed as 'sprinting' in Table 1. Pedal cadence of 76 RPM was chosen since that was the cadence of the climbing scenario (see next paragraph), and is not an unreasonable cadence for a high-gear, flat-ground sprint.

The value of 1609W of power at the pedals for the sprinting scenario was estimated here by scaling the 665W of power for the climbing scenario by the ratio of the chain tension for the sprinting scenario to that of the climbing scenario. 1609W for the sprinting scenario places it within the range of world class sprinters. Since the rider who performed the tests was an amateur road racer it is likely the actual level of power output at the pedals was lower.

Table 1 does not include the forces acting on the bottom bracket shell that would occur due to the forces on the pedal and cranks. Instead, it was decided to simulate the bottom bracket shell as being rigidly clamped as seen in Figure 7. This approach causes the FEA software to internally calculate the reaction forces acting on the bottom bracket shell necessary to counterbalance the forces in Table 1. For the purpose of calculating energy and power required to flex a frame the results are extremely close to that of directly entering the forces acting on the bottom bracket shell, with the advantage that the the amount of front and rear triangle flex may be directly entered into Equations 2 and 3 without the additional step of subtracting out the relative position of the bottom bracket shell.

It is noted the chosen approach could introduce meaningful levels of error when simulating stresses at the bottom bracket weld joints. This is because when the FEA software simulates the bottom bracket being clamped, doing so prevents the bottom bracket itself from deforming when stressed. In light of that for the purposes of estimating frame flexibility of the front and rear triangles relative to the bottom bracket such differences do not impact the findings in any meaningful manner, especially since the reference frame went through the additional step of being calibrated.

As a separate analysis the power associated vertical frame flex was estimated for the climbing scenario. In the climbing scenario the rider is not seated thus their lower torso and legs move upward and downward with each half pedal stroke. For the climbing scenario only Soden (1979) reported the vertical acceleration of the cyclist's lower torso as 1.6 times that of gravity (i.e., 1.6 g). This means 1.6 times the force of the cyclist's body pushes vertically downward on the pedals each time one of the pedals reaches its lowest 6:00 position.

For clarity, the 6:00 pedal position is where the maximum downward acceleration of the rider's body occurs from the rider's body bobbing up and down. At the 6:00 position there is no crank arm leverage thus the chain tension is zero, or very close to zero. In contrast, the 3:00 pedal position is the point of maximum downward pedal force with maximum crank arm leverage, thus maximum chain tension causing maximum rear triangle flex.

The analysis of vertical frame flex at a pedal position at 6:00 conservatively ignored that the cyclist's arms, head, and upper torso are relatively vertically stable when climbing since the cyclist's hands are gripping the handlebars, and instead assumed the rider's entire body mass moved vertically up and down. Even with this conservative assumption the FEA analysis confirmed a very small amount of vertical flex at the bottom bracket as expected, resulting in less than 0.1 Watts of power associated with the vertical flex. This is 89 times less than the power required to flex a frame for the climbing scenario in Table 2. For these reasons the power associated with vertical flex was excluded from all findings in this report.

3. Results

Table 2 shows the resulting deflections in the direction of each force, resulting energy and power associated with frame flex, and the

percentage of power required to flex a frame relative to the power output at the pedals. The cyclist's power required to flex a frame was found to be 1.6, 9.0, and 47 Watts respectively for the speeding, climbing, and sprinting scenarios. As a percentage of the power output at the pedals, the cyclist's power required to flex a frame was found to be 0.65, 1.3, and 2.9 percent. These results are meant to be representative of an on-road bicycle frame with average front and rear triangle flexibility.

Table 2. Frame deflections and associated cyclist's energy and power.

	Speeding	Climbing	Sprinting
Frame Deflections (mm)			
Right Handlebar (up)	1.8	4.9	15
Left Handlebar (down)	5.0	12	24
Rear Cog (direction of chain tension)	0.9	2.4	4.9
Energy Required To Flex Front Triangle			
Right Handlebar (Joules)	0.06	0.58	5.4
Left Handlebar (Joules)	0.25	1.1	3.5
Total (Joules)	0.32	1.6	8.9
Energy Required To Flex Rear Triangle			
Rear Cog (Joules)	0.2	1.9	9.7
Total Energy Required To Flex Frame	0.5	3.5	19
Power Required To Flex Front Triangle			
Right Handlebar (Watts)	0.19	1.5	14
Left Handlebar (Watts)	0.76	2.7	8.8
Total (Watts)	0.95	4.1	23
Power Required To Flex Rear Triangle			
Rear Cog (Watts)	0.65	4.8	24
Total Power Required To Flex Frame (Watts)	1.6	9.0	47
Percent of Power at the Pedals	0.63%	1.3%	2.9%

To estimate the cyclist's power required to flex the stiffest frame the ratio of the least flexible front and rear triangles to that of the average front and rear triangles were used to scale the results above. Since frame stresses are modeled as remaining within the material's Yield Strength the deflection varies linearly with force applied. Similarly, the power required to flex the most flexible frame can be estimated. The results are that the power required to flex the stiffest frame is about 50 percent less than the average, 0.72, 4.3, 22 Watts for the three scenarios. The power required to flex the most flexible frame is about 50 percent greater than the average, 2.4, 13, 69 Watts.

For cyclists concerned about the power penalty of a more flexible frame, as working numbers we can estimate the maximum power penalty as the difference between the power required to flex the most flexible to that of the stiffest. Those differences for the speeding, climbing, and sprinting scenarios are 1.7, 8.9, and 47 Watts representing 0.6, 1.3, and 2.9 percent of the power at the pedals. These results coincidentally are numerically closely matched with the power associated with a frame of average flexibility.

To put this into perspective, Table 3 demonstrates that the maximum power penalty to flex a frame is less than the drivetrain losses of the most efficient drivetrains up to an estimated 820 Watts of power at the pedals.

Table 3. Maximum power penalty of the most flexible frames relative to the stiffest frames, versus power losses of the most efficient drivetrains.

	Speeding	Climbing	Crossover	Sprinting
Power at the Pedals (Watts)	255	665	**820**	1609
Percent Power at the Pedals				
Maximum Power Penalty to Flex Frame	0.6%	1.3%	**1.6%**	2.9%
Drivetrain Power Losses (highest efficiency)	2.3%	1.7%	**1.6%**	1.4%

To construct Table 3 drivetrain power loss data was consulted (CERAMICSPEED, 2025). Drivetrain losses vary linearly with power output at the pedal, and from this drivetrain power losses in Table 2 were interpolated and extrapolated along a best fit line. It was found that up to an estimated 820 Watts of power output at the pedals, the maximum power penalty is less than drivetrain losses for the most efficient drivetrains. The Crossover column in Table 3 represents where the maximum power penalty equals drivetrain losses.

It should be noted that the metabolic muscle power exerted by the cyclist's upper torso and arms upon the handlebars as a form of leverage to increase the net downward force on the pedals (which would occur regardless of frame flex), no doubt far exceeds the incremental power of incrementally flexing the front triangle. Thus, in Table 2 and 3 the power required to flex the frame as a percentage of the

cyclist's power at the pedals is conservatively high since the upper body metabolic muscle power was not included from the reported power at the pedals.

4. Discussion and Applications

For cyclists interested in knowing how much of the power required to flex a frame is returned to the rear wheel as forward motion when the frame un-flexes, it is proposed to be at most 40 percent. In Table 2 the energy, thus power, to flex a frame is roughly divided 50/50 between the front and rear triangles. In the case of the front triangle, let's assume that the power returned by the front triangle cannot travel the length of the cyclist's body to the pedals. So, 50 percent of the total power penalty of flexing the frame is lost within the front triangle.

In the case of the rear triangle, let's assume the only loss is a 10 percent internal hysteresis loss as mentioned in Section 2.1. If this were the only loss for the rear triangle then at most 40% of the total power penalty (front and rear) can be recovered as forward motion. Whether or not the 40% figure is in fact lower was not further speculated.

These findings might hopefully encourage research into aspects of frame flex on their own merit free from the presumption that the power penalty for flexing a frame is relatively high, whereas this report indicates power penalty is less than the power losses of the most efficient drivetrains up to about 800+ Watts of power at the pedals.

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Conflicts of Interest: The author declares no conflicts of interest.

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